Searching for primordial features from CMB and LSS surveys

collab. with A. Achucarro, V. Atal, P. Ortiz, J. Torrado

[PRD 89 (2014) 103006]
[PRD 90 (2014) 023511]
[arXiv:1410.4804]

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Outline

1. Observational hints of oscillatory features
2. Models with a transient reduction of the speed of sound
3. Search with CMB map
4. Search with LSS survey
5. Conclusion
Planck-2013: Great success of base-LCDM & single-field slow-roll inflationary model
1. Observational hints of oscillatory features

TT spectrum residual from best-fit LCDM model

[Planck-2013: XXII]
Spectrum residual from best-fit LCDM model

\[ l \in (500, 1200) \]

 Appears in all channels
Observational hints of oscillatory features

2. CMB bispectrum

\[ B(k_1, k_2, k_3) = \frac{6 A^2 f_{\text{NL}}^{\text{feat}}}{(k_1 k_2 k_3)^2} \sin \left( 2\pi \frac{\sum_{i=1}^{3} k_i}{3 k_c} + \phi \right) \]

The best-fit template to the reconstructed CMB bisp \sim 3\sigma detection

<table>
<thead>
<tr>
<th>Wavenumber ( k_c ); phase</th>
<th>( \Delta k = 0.015 )</th>
<th>( \Delta k = 0.03 )</th>
<th>( \Delta k = 0.045 )</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01125; ( \phi = 0 ) . .</td>
<td>765 ± 275 (2.8)</td>
<td>703 ± 241 (2.9)</td>
<td>648 ± 218 (3.0)</td>
<td>434 ± 170 (2.6)</td>
</tr>
<tr>
<td>0.01750; ( \phi = 0 ) . .</td>
<td>-661 ± 234 (-2.8)</td>
<td>-494 ± 192 (-2.6)</td>
<td>-425 ± 171 (-2.5)</td>
<td>-335 ± 137 (-2.4)</td>
</tr>
<tr>
<td>0.01750; ( \phi = 3\pi/4 ) . .</td>
<td>399 ± 207 (1.9)</td>
<td>438 ± 183 (2.4)</td>
<td>442 ± 165 (2.7)</td>
<td>366 ± 126 (2.9)</td>
</tr>
<tr>
<td>0.01875; ( \phi = 0 ) . .</td>
<td>-562 ± 211 (-2.7)</td>
<td>-559 ± 180 (-3.1)</td>
<td>-515 ± 159 (-3.2)</td>
<td>-348 ± 118 (-3.0)</td>
</tr>
<tr>
<td>0.01875; ( \phi = \pi/4 ) . .</td>
<td>-646 ± 240 (-2.7)</td>
<td>-525 ± 189 (-2.8)</td>
<td>-468 ± 164 (-2.9)</td>
<td>-323 ± 120 (-2.7)</td>
</tr>
<tr>
<td>0.02000; ( \phi = \pi/4 ) . .</td>
<td>-665 ± 229 (-2.9)</td>
<td>-593 ± 185 (-3.2)</td>
<td>-500 ± 160 (-3.1)</td>
<td>-298 ± 119 (-2.5)</td>
</tr>
</tbody>
</table>

[Planck-2013: XXIV]
Main results

1. A transient reduction of sound speed generically gives primordial oscillatory features.

2. It could produce sizeable and distinguishable features in CMB spectrum, bispectrum and matter spectrum.

3. Planck-2013 and WiggleZ data shows a coincidence in the best-fit mode.

4. The statistical significance is not big enough to claim a detection.

5. Based on our best-fit mode from power spectra, we have a specific prediction on the bispectrum, and we are waiting for Planck-2014(5) test.
2. Models with a transient reduction of the speed of sound

Assumption: 1 light & 1 heavy fields

Two field model:
\[ S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} R - \frac{1}{2} g^{\mu\nu} \gamma_{ab} \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi) \right] \]

EFT for inflation:
- Light adiabatic
- Heavy isocurvature

Derivative coupling, e.g. \( \dot{\phi}_1 \phi_2 \Rightarrow \text{a turn} \)

References:
- C. Cheung et. al. JHEP 0803 (2008) 014
- A. Achucarro et. al. JHEP 1205 (2012) 066

\[ \phi^a(t, x) = \phi_0^a(t + \pi) + N^a(t + \pi) \mathcal{F} \]
After Integrating out heavy field effective action for light field:

\[
S_{\text{eff}} = - \int d^4x \, a^3 M_{\text{pl}}^2 \dot{H} \left\{ \dot{\pi}^2 - \frac{(\nabla \pi)^2}{a^2} + (c_s^{-2} - 1) \dot{\pi}^2 + (c_s^{-2} - 1) \dot{\pi} \left[ \ddot{\pi}^2 - \frac{(\nabla \pi)^2}{a^2} \right] + (c_s^{-2} - 1)^2 \frac{\dot{\pi}^3}{2} - 2 \frac{\dot{c}_s}{c_s^3} \pi \dot{\pi}^2 + \cdots \right\}
\]

slow roll sound speed

Primordial sprectrum: \( P_R \propto \mathcal{O}(\epsilon) + \mathcal{O}\left(\epsilon(1 - c_s^{-2})\right) \) sub-leading

Primordial bispectrum: \( \mathcal{B} \propto \mathcal{O}\left(\frac{\dot{c}_s}{Hc_s}\right) + \mathcal{O}(\epsilon) \) leading

\( \epsilon \sim \mathcal{O}(0.01) \) \( 1 - c_s^{-2} \sim \mathcal{O}(0.1) \) \( \frac{\dot{c}_s}{Hc_s} \sim \mathcal{O}(0.1) \)

Do NOT interrupt slow roll condition!
Oscillatory features in the transient sound speed reduction models—Power spectrum

\[ \frac{\Delta P_R(k)}{P_R} = k \int_{-\infty}^{0} d\tau \left(1 - c_s^{-2}\right) \sin(2k\tau) \]

Gaussian reduction in e-folds

\[ 1 - c_s^{-2} = B e^{-\beta \left(\log \frac{\tau}{\tau_0}\right)^2} \]

[\text{A.Achucarro et. al. PRD 89 (2014) 103006}]

Keep slow roll condition
Some examples ($B = -0.1$)
\[ \frac{\ell (\ell + 1)}{2\pi^2} \frac{\Delta C_{\ell}^{TT}}{C_{\ell}^{TT}} (\mu K^2) \]

\[ \frac{\ell (\ell + 1)}{2\pi^2} \frac{\Delta C_{\ell}^{EE}}{C_{\ell}^{EE}} (\mu K^2) \]

\[ \frac{\ell (\ell + 1)}{2\pi^2} \frac{\Delta C_{\ell}^{T\ell}}{C_{\ell}^{T\ell}} (\mu K^2) \]

\[ \frac{\ell (\ell + 1)}{2\pi^2} \frac{\Delta C_{\ell}^{E\ell}}{C_{\ell}^{E\ell}} (\mu K^2) \]

\[ \text{Multipole, } \ell \]

\[ \text{Multipole, } \ell \]

\[ \sim 10\% \text{ effect} \]
2. Primordial Bispectrum (leading order)

\[ B(k_1, k_2, k_3) = \frac{6\Delta_2^2}{k_1 k_2 k_3} \frac{(2\pi)^4}{96} \left| B \right| D_s(K) k_1^2 \]

\[ D_s(K) = -\sqrt{\frac{\pi}{\beta}} 2K \tau_0 \exp\left( -\frac{K^2 \tau_0^2}{4\beta} \right), \quad K = k_1 + k_2 + k_3 \]

\[ \left\{ \tau_0 \cos(\tau_0 K) \left[ k_2(k_1 - k_3) + \frac{\tau_0^2}{2\beta} K k_2 k_3 \left( \frac{3}{2} k_1 - k_2 \right) - \frac{1}{2\beta} \left( \frac{1}{2} k_1^2 - k_2^2 \right) \right] \right. \]

\[ + \sin(\tau_0 K) \left[ \frac{1}{2} \tau_0^2 k_1 k_2 k_3 - \frac{1}{K} \left( \frac{1}{2} k_1^2 - 2k_2^2 \right) - \frac{\tau_0^2}{2\beta} k_2 \left( 2k_1^2 - k_2 k_3 \right) \right] \} + 5 \text{ perm.} \]

\[ K = 0.19 \quad K = 0.21 \quad \text{removing} \quad \frac{1}{k_1^3 k_2^3} + \frac{1}{k_1^3 k_3^3} + \frac{1}{k_2^3 k_3^3} \]

Step in sound speed:

\[ l_1 = 4, l_3 = l_2 + 4 \]

\[ l_2 \] 0.5
\[ 1\times10^8 \, [\mu K^3] \]

**single field slow roll:**

- ISWL
- local \((f_{NL}=10)\)
- Sound speed model \((|B|=0.1, \log(-\tau_0)=5.55, \log(\beta)=7.15)\)
- sin model \((f_{NL}=10^6, k_c=0.01, \phi=0)\)

\[ f_{NL}^{\text{local}} \sim 0.01 \]
$l_1 = l_2 = l_3$ equilateral

Also see Munchmeyer’s & Van Tent’s talks

local ($f_{NL}=1$)

Sound speed model ($|B|=0.1$, $\log(-\tau_0)=5.55$, $\log(\beta)=7.15$)

sin model ($f_{NL}=10^3$, $k_c=0.01$, $\phi=0$)

preliminary
Other studies and searches for features in the CMB Power spectrum and bispectrum

Linear oscillation (e.g. step-like features in V)

Log-spaced oscillation (e.g. monodromy inflation)

Others sources of features
(e.g. multi-field dynamics, non-Bunch-Davis vacuum)

And, of course, Planck's team search for features:
Ade et al. (2013) "Constraints on Inflation"
3. Search with CMB map—TT spectrum

profile likelihood

<table>
<thead>
<tr>
<th></th>
<th>$-B \times 10^2$</th>
<th>$\ln \beta$</th>
<th>$\ln(-\tau_0)$</th>
<th>$\Delta \chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(4.5) 3.7 $^{+1.6}_{-3.0}$</td>
<td>(5.7) 5.7 $^{+0.9}_{-1.0}$</td>
<td>(5.895) 5.910 $^{+0.027}_{-0.035}$</td>
<td>-4.3</td>
</tr>
<tr>
<td>B</td>
<td>(4.2) 4.3 $\pm 2.0$</td>
<td>(6.3) 6.3 $^{+1.2}_{-0.4}$</td>
<td>(5.547) 5.550 $^{+0.016}_{-0.015}$</td>
<td>-8.3</td>
</tr>
<tr>
<td>C</td>
<td>(3.6) 3.1 $^{+1.6}_{-1.9}$</td>
<td>(6.5) 5.6 $^{+1.9}_{-0.7}$</td>
<td>(5.331) 5.327 $^{+0.026}_{-0.034}$</td>
<td>-6.2</td>
</tr>
<tr>
<td>D</td>
<td>(4.4)</td>
<td>(6.5)</td>
<td>(5.06)</td>
<td>-3.3</td>
</tr>
</tbody>
</table>

Also see Meerburg’s talk.

degeneracy of featured and vanilla parameters is negligible.
4. Search with LSS survey—WiggleZ

features shows around $k \sim (0.1, 0.2)$

Search up to $k = 0.2$
Independent search with different data

Planck+WP

WiggleZ
Independent search with different data

Planck+WP

WiggleZ

Two coincident modes including the best-fit mode
Combine Planck and WiggleZ

get better constrained in Planck+WiggleZ
Bayesian Evidence

Evidence: \[ Z = \int \mathcal{L}(D|M(\theta)) \pi(\theta) \, d^D\theta \]

\[ M_0 : \text{ Base-LCDM model } \quad M_1 : \text{ Sound speed model} \]

\[ R < 1: \text{ data favors } M_0 \quad R > 1: \text{ data favors } M_1 \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Data set</th>
<th>(-2 \ln \mathcal{L})</th>
<th>(\ln Z)</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_1)</td>
<td>Planck</td>
<td>9801.918 (9796.27)</td>
<td>(-4955.61 \pm 0.31)</td>
<td>(\exp(0.46) \approx 1.6)</td>
</tr>
<tr>
<td>(M_0)</td>
<td>Planck</td>
<td>9807.154 (9805.90)</td>
<td>(-4956.07 \pm 0.31)</td>
<td></td>
</tr>
<tr>
<td>(M_1)</td>
<td>Planck+WiggleZ</td>
<td>10253.570 (10249.20)</td>
<td>(-5183.05 \pm 0.32)</td>
<td>(\exp(0.62) \approx 1.9)</td>
</tr>
<tr>
<td>(M_0)</td>
<td>Planck+WiggleZ</td>
<td>10262.042 (10258.80)</td>
<td>(-5183.67 \pm 0.31)</td>
<td></td>
</tr>
</tbody>
</table>

Jeffreys’s criterion (1<\(R<3\)): Barely worth mentioning!
1. A transient reduction of the speed of sound generically gives primordial oscillatory features.

2. It could produce sizeable and distinguishable features in CMB spectrum, bispectrum and matter spectrum.

3. Planck-2013 and WiggleZ data shows a coincidence in the best-fit mode.

4. The statistical significance is not big enough to claim a detection.

5. Based on our best-fit mode from power spectra, we have specific prediction on the bispectrum, and we are waiting for Planck-2014(5) test.
Thanks for your attention!
Merry Xmas to Planck!
bonus slide
Two mode with the same frequency $\log(-\tau_0) = 5.5$
but with different location $\log(\beta) = 6.3$ (red) $\log(\beta) = 7.2$ (green)
Primordial power spectrum

Log $\tau_0=5.5$, Log $\beta=6.3$

Log $\tau_0=5.5$, Log $\beta=7.2$
After convolving with transfer function they look similar, due to the damping effect on small scale.

Log $\tau_0=5.5$, Log $\beta=6.3$/before filtering
Log $\tau_0=5.5$, Log $\beta=7.2$/before filtering
Log $\tau_0=5.5$, Log $\beta=6.3$/after filtering
Log $\tau_0=5.5$, Log $\beta=7.2$/after filtering
Some examples ($B = -0.1$)
Some examples \((B = -0.1)\)
Some examples \( (B = -0.1) \)
3. Search with CMB map—TT spectrum

profile likelihood

Planck+WP
degeneracy with vanilla parameter is negligible

CoV Mat
Search with CMB map—Zoom in best-fit

Need to consider look-elsewhere effect!

Enlarge the parameter space
2. Models with a transient reduction of the speed of sound

\[ S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} R - \frac{1}{2} g^{\mu\nu} \gamma_{ab} \partial_{\mu} \phi^{a} \partial_{\nu} \phi^{b} - V(\phi) \right] \]

\[ \phi^a(t, x) = \phi_0^a(t + \pi) + N^a(t + \pi) F \]

light adiabatic \hspace{1cm} heavy isocurvature

integrating out \hspace{1cm} heavy field

effective action:

\[ S = \frac{1}{2} \int d^4 x \phi_0^2 \left\{ c_s^{-2} \dot{\pi}^2 - (\nabla \pi)^2 + \left( \frac{1}{c_s^2} - 1 \right) \dot{\pi} [\dot{\pi}^2 - (\nabla \pi)^2] + \left( \frac{1}{c_s^2} - 1 \right)^2 \frac{\dot{\pi}^3}{2} \right\} + 2 \frac{\dot{\phi}_0}{\phi_0} \left[ \frac{\dot{\pi}^2}{c_s^2} - (\nabla \pi)^2 \right] \pi - 2 \frac{\dot{c}_s}{c_s^3} \dot{\pi}^2 \pi \],

\[ c_s^2 \]

sound speed reduced

Time
4. Search with LSS survey—WiggleZ

features shows around $k \sim (0.1, 0.2)$

Search up to $k=0.2$